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Summary

The general approach and products of the NASA/FAA Airborne Windshear Program conducted by NASA Langley Research Center are summarized, with references provided for the major technical contributions. During this period, NASA conducted 2 years of flight testing to characterize forward-looking sensor performance.

The NASA/FAA Airborne Windshear Program was divided into three main elements: Hazard Characterization, Sensor Technology, and Flight Management Systems. Simulation models developed under the Hazard Characterization element are correlated with flight test data. Flight test results comparing the performance and characteristics of the various Sensor Technologies (microwave radar, lidar, and infrared) are presented. Most of the activities in the Flight Management Systems element were conducted in simulation. Simulation results from a study evaluating windshear crew procedures and displays for forward-looking sensor-equipped airplanes are discussed.

NASA Langley researchers participated heavily in the FAA process of generating certification guidelines for predictive windshear detection systems. NASA participants felt that more valuable technology products were generated by the program because of this interaction. NASA involvement in the process and the resulting impact on products and technology transfer are discussed in this paper.

Introduction

Windshear refers to a wind speed or direction change experienced by an airplane over a particular distance or length of time. Most windshear is not sufficiently strong enough to be hazardous to an airplane in flight. A certain subset of windshears, however, may be of critical impact to flight safety during low-altitude, low-speed flight. An airplane in the takeoff and landing phases of flight has minimal excess energy since both altitude and airspeed are low. Moreover, a typical airline transport airplane cannot quickly change its energy state in this flight phase due to the time required to reconfigure high-lift devices and landing gear, as well as the time required to reach maximum rated thrust (particularly with modern high bypass turbofans). In these critical phases of flight, the option to trade altitude for airspeed is minimal or not available at all.

A flight safety hazard exists if a sustained energy-reducing windshear (decreasing headwind, downdraft, or increasing tailwind) takes away airplane energy faster than engine thrust can add it back. In such a condition, the airplane is forced to either lose airspeed or descend. Given a low-airspeed, low-altitude initial condition, either option may be hazardous.

A weather condition known as a microburst can generate hazardous low-altitude windshear. A microburst is formed when a column of air at high altitude quickly cools due to evaporation of ice, snow, or rain. This cooling air becomes denser than the surrounding atmosphere and falls rapidly to the ground. Upon nearing the ground, the downward moving air spreads rapidly in all directions away from the descending core. Windspeed changes in excess of 40 meters per second (80 knots) over 4 kilometers have been recorded in such events.

Inadvertent encounters with low-altitude windshear have been a major cause of transport airplane accidents and passenger injuries and fatalities. Since 1964, windshear has been a causal factor in at least 26 U.S. air carrier accidents, resulting in over 500 fatalities and 200 injuries. In 1986, NASA and the FAA signed a Memorandum of Agreement (MOA) establishing the NASA/FAA Airborne Windshear Program to investigate the feasibility of remote airborne windshear detection. In 1990, this MOA was expanded to include the integration of both airborne and ground-based windshear measurement information.

This paper describes the structure and overall results of the NASA/FAA Airborne Windshear Program. More detailed and complete technical descriptions of the program's research activities and products are available in the publications listed in the bibliography.

Hazard Characterization

This element of the program was aimed at understanding the detailed characteristics and complete nature of the hazard posed by convective storm microbursts when encountered at low altitudes by jet transport airplanes.

Several of the technology developments in this element of the program were the foundation upon which the entire program was built. The Terminal Area Simulation System and development of the "F-factor" (see Airplane Hazard Index) enabled the other activities to occur. Vertical Wind Estimation was based on an understanding of microburst flow structure and allowed forward-look Doppler sensors to estimate the full 3-D hazard from a 2-D measurement. Heavy Rain was investigated to define any airplane performance penalties that occur during microburst encounters involving high rainfall rates.

Terminal Area Simulation System

The Terminal Area Simulation System (referred to as TASS throughout the remainder of this paper and also known as the "NASA Windshear Model") was developed in the mid-80's under contract to NASA Langley Research Center.[22,23] TASS is a three-dimensional, time-dependent, cloud model which includes parameterizations for both liquid- and ice-phase microphysics. The treatment of water substances in the model allows for condensation, evaporation, freezing, and sublimation, including subsequent latent heat exchanges.

Given an initial atmospheric sounding (vertical profile of ambient temperature, dewpoint, and wind velocity) and an initial triggering impulse, TASS can numerically simulate the time-dependent life-cycle of a convective storm, including any subsequent microburst(s) that may develop.

The TASS model has been applied to a diversity of microburst cases, including the 1985 DFW (Dallas/Ft. Worth) event that resulted in the crash of an L-1011 on approach,[25] the 1988 and 1989 Denver events that resulted in one or more "close calls" for airplanes on approach,[28,27] a 1991 Orlando event that was deliberately penetrated by an instrumented NASA research airplane,[4] and the 1994 Charlotte event that resulted in the crash of a DC-9 on approach.[29] In all of these cases, TASS has demonstrated the ability to produce simulations of events that compare well with actual observations.

During the NASA/FAA Airborne Windshear Program (and subsequently), TASS was used in four valuable ways: (1) to aid in understanding the "science" of microburst events; (2) to aid in reconstructing an event and filling in "holes" or providing variables unavailable from observations; (3) to provide a means for "testing" and evaluating sensor capabilities using simulation; and (4) for use with flight simulator studies to evaluate "what if" scenarios. References 1-5, 22-29, and 31 provide details on TASS.

Airplane Hazard Index

An airplane flying through the center of a microburst first experiences a performance-enhancing increasing headwind that is rapidly followed by a performance-decreasing sequence of decreasing headwind, then downdraft, and finally increasing tailwind. A metric termed "F-factor" was developed by NASA researchers to quantify the airplane performance loss that a specific windshear produces.[7] As a nondimensional "atmospheric" term that was added to the standard $\gamma_p = (T - D)/W$ airplane performance equation, the F-factor indicates the equivalent specific excess thrust (thrust minus drag divided by weight) required to maintain steady flight conditions due to wind variations. Since a typical twin-engine jet transport airplane may have engines capable of producing a specific excess thrust of 0.17, a microburst which produced a sustained windshear with intensity greater than an F-factor of 0.17 would exceed the maximum performance capability of that airplane. Upon encountering such a windshear, this airplane would be forced to either lose airspeed, altitude, or both, regardless of pilot control strategy or inputs.

An important consideration in determining the impact of a given windshear or F-factor level is the length of time over which the airplane is exposed to the windshear. For a given airspeed, this exposure time can be converted into a distance. Very quick wind changes (which occur over a short distance) are categorized as turbulence rather than hazardous windshear. Although turbulence can indeed be a safety issue, it is more because of controllability or airplane structural impact than airplane energy loss considerations. Windshears which are of importance to the energy state of an airplane operating at low altitude are those which result in F-factor values near the maximum excess thrust of a particular airplane and which persist at that average magnitude for a significant period of time (see below).

Reactive, or in-situ, systems cannot predict the scale length of a windshear. These systems must therefore rely on real-time calculation of F-factor from airplane measurements and apply gust rejection filters to minimize nuisance alerts (from short scale length wind variations typically classified as turbulence). Many forward-looking windshear detection technologies can determine the spatial extent of windshear before an encounter. For an accurate predictive warning of a hazardous encounter, the forward-looking system must determine the spatial extent of the hazard area and relate this to an estimate of airplane exposure based on the current airspeed. An analytical study conducted by NASA researchers[19] concluded that the best results for forward-looking system hazard computation were achieved when F-factor was averaged over one kilometer. The one kilometer averaging length translates into approximately 15 seconds of exposure at typical jet airplane low-altitude airspeeds (135 knots). In this paper, "F-BAR" is used as F-factor averaged over 1 kilometer.

Vertical Wind Estimation

Both radar and lidar technologies function by measuring the Doppler shift in backscattered microwave or optical energy from atmospheric particulates (rain drops, aerosols, etc.) to determine the line-of-sight relative velocity of the air. An inherent limitation of this approach is its inability to measure velocities that are perpendicular to the line-of-sight. The presence of a microburst can be detected by measuring the divergence of the horizontal velocity profile; however, failure to measure or calculate the downdraft can result in a significant underestimate of the magnitude and spatial extent of the hazard.[35]

One solution to the line-of-sight limitation of Doppler sensors is to use a theoretical or empirical model of a microburst to estimate the perpendicular velocities from the measured line-of-sight values. This was the approach used by NASA. A "buildup" series of studies was conducted to: develop a set of candidate downdraft estimation models; evaluate the characteristics of these models; and assess the approach and promising models in a realistic microburst environment (both simulation and flight test).[34-36]

The results of these studies indicate that, in the altitude region of interest (at or below 300 meters), simple vertical wind estimation models (based on mass continuity) provided an accurate hazard estimate. More elaborate vertical wind estimation models provided an improved hazard estimate relative to the simpler techniques. The degree to which the hazard estimate was improved varied with altitude, with maximum improvement occurring at about 300 meters. At lower altitudes, the improvement was minimized by the diminished contribution of the vertical wind as the ground is approached.[36]

Heavy Rain Effects

Microbursts in the eastern U.S. are often associated with a rain-producing convective storm. The effect of rain on airplane performance under normal conditions is considered insignificant. However, when an airplane encounters a windshear requiring maximum airplane performance, the influence of heavy rain may be a factor.

NASA Langley Research Center conducted a series of experimental and analytical studies to quantify the effects of heavy rain on airplane performance, with emphasis on flight conditions expected in a microburst encounter. The most visible of these experiments were tests of a full-scale NACA 64-210 airfoil under simulated rainfall conditions at Langley Research Center's Aircraft Landing Dynamics Facility.

The results from these studies documented a reduction in the maximum lift capability and stall angle-of-attack, with a corresponding increase in drag, as rain concentrations were increased. In extremely heavy rain conditions, climb performance margin reductions equivalent to an F-factor of about 0.01 were estimated.[33] A performance loss of this degree can impair an airplane's ability to recover from a microburst windshear encounter under certain conditions.

Sensor Technology

Studies in the Flight Management element determined that a forward-look sensor system must detect a microburst event at least 10 seconds before entering the event to achieve significant flight safety benefits.[13,14] This advance warning requirement was used in forward-looking sensor technology development.

The general approach of this program element was to develop various airborne detection technology options using TASS data sets coupled with simulation models of the sensor. Once the sensor technology demonstrated its simulation performance against the TASS microburst data sets, it became a candidate for flight test validation. The infrared device was independently developed and did not follow this development approach. In 1991 and 1992, those sensor technologies that were "ready" were all installed on the NASA Langley Research Center B-737 Transport Systems Research Vehicle (TSRV) and flown into known microburst conditions (see Flight Test Validation) to evaluate and compare sensor performance.

The "in-situ" (or reactive) algorithm was developed in this program element since it served as the baseline measurement against which some key sensor performance characteristics were measured. The infrared device was pursued as a simple, cheap technology for microburst detection. Both Doppler radar and lidar technologies were pursued since each technology's strength was the other's weakness, in the context of the need to detect both "dry" and "wet" microburst events (see Radar).

In-situ

Although airborne in-situ windshear detection systems have been available and in service for at least 5 years, many are based on a two-dimensional analysis of the hazard index measurement that assumes flight in the vertical plane. Because of this restriction, the accelerations resulting from normal airplane maneuvering can produce erroneous hazard calculations, for which compensation must be made. In particular, errors can occur due to turns, thrust changes, and nonhazardous wind conditions.

One of the major goals in developing the NASA in-situ algorithm/system was to eliminate these problems through development and implementation of a generalized three-dimensional algorithm. This generalized implementation would advance the in-situ sensor technology by providing a measurement with low nuisance alert rate, expanded operating envelope, and additional implementation flexibility. Another major motivator for a generalized implementation was to provide a measurement standard for forward-look sensor validation (see Flight Test Validation).

This algorithm calculated the vertical, horizontal, and total F-factor of an airplane's current environment based upon airspeed, accelerometer, angle-of-attack, groundspeed, and other airplane sensor inputs. The algorithm included filtering equations to reduce turbulence feed-through.[21]

The in-situ algorithm was extensively tested both in piloted simulation and in a hot bench laboratory utilizing flight software code. Following this development effort, the software was implemented on the TSRV's research computers for real-time operation. Flight tests proved the immunity of the algorithm to aircraft maneuvering (steep turns in strong winds and normal acceleration) as well as rapid thrust and drag changes. A display of algorithm outputs was also designed and implemented on the research airplane to allow real-time monitoring of windshear levels encountered during microburst penetrations.

During the 1991 and 1992 flight tests, all in-situ algorithm hazard computations appeared to correlate well with airplane performance. No false in-situ alerts were generated, no nuisance alerts were generated, and 18 valid hazard alerts were annunciated. For additional operational details, see Flight Test Validation.

Infrared

Since a microburst occurs when a mass of cool air aloft rapidly descends through warmer ambient air, a temperature gradient is typically experienced by an airplane penetrating a microburst. It was postulated that a forward-looking infrared device could sense temperatures well ahead (~5 km) of an airplane and identify a thermal signature associated with a microburst. This hypothesis relies upon the assumption that there is a correlation between the sensed thermal signature and the windshear hazard of the microburst. If nonhazardous atmospheric conditions yield the same type of temperature signature, then this approach is problematic from an operational point of view.

An instrument developed by Turbulence Prediction Systems (with partial funding from a NASA Small Business Innovative Research contract) was installed in a forward cabin window and sensed atmospheric infrared energy through a small periscope assembly. A hazard index based upon the differential between long-range (3-5 km) and ambient temperature was computed within the device and recorded on the TSRV's data system.

The 1991 and 1992 flight tests collected an extremely large data set. NASA's limited analysis of this data set clearly indicated the difficulties in determining an empirical relationship between passive temperature measurements and windshear hazards.[5] It is not clear whether such a relationship could be made sufficiently robust to provide both acceptable detection and false alarm performance. Although the infrared system detected several microbursts, no direct relationship between temperature change and F-factor was ever determined. In some atmospheric conditions microbursts may actually create a slight temperature rise at the airplane approach altitude[31] and other phenomena may create cooling without producing a hazardous windshear. In addition, the infrared device suffered similar rain attenuation characteristics as those described for the CO_2 lidar (below).

Radar

The primary goal for the airborne radar was real-time remote detection of windshear from "wet" or "dry" (defined as having a radar reflectivity less than 35 dBZ) microbursts. At microwave frequencies, absolutely clear air produces only very small returns from wavelength-scale gradients in the index of refraction. The emphasis in airborne radar development was on those microbursts containing at least some liquid water. At the beginning of this program, previous work indicated that it was feasible for an airborne radar to detect the presence of windshear.[11] However, for operational airplane landing and takeoff applications, the problems of severe ground clutter, rain attenuation, and low reflectivity levels had to be solved.

Performance requirements used by radar system designers for windshear detection included:

(a) wind measurements with an accuracy of about 1 m/s;
(b) range measurement resolution of 150-300 meters;
(c) total range of 5-10 km; and
(d) sector scan of approximately ±30° centered about the airplane flight path.

Extensive trade-off and performance studies were conducted[8] to assess the capability of an airborne radar to meet performance and operational requirements. X-band (8-12 GHz) was selected as the near optimum operating frequency range for this radar. It was chosen over S-band (1-3 GHz) or C-band (3-8 GHz) primarily because of the increase in sensitivity and smaller cell resolution, which outweighed the small increase in attenuation (2-5 dB) experienced for wet microbursts. An X-band system also performs better for low reflectivity (dry) microbursts. The choice of a 9.3 GHz system was also influenced by the fact that most commercial airlines currently use X-band systems for airborne weather radar. With the incorporation of suitable design improvements and signal processing algorithms, it was felt that these commercial radars could be made to provide the windshear detection function.

A key tool in the successful development of NASA's research radar system was a comprehensive simulation of the radar and ground clutter models. This model was used to investigate signal processing methods required to allow an airborne radar to accurately detect and measure hazardous windshear.[9] Synthetic aperture radar data from multiple airport sites were collected and stored in a database that was used to model stationary ground clutter. Moving ground clutter targets were modeled on the roads and highways surrounding the airport terminals and approach corridors. Using these ground clutter sources, radar design parameters were systematically varied to determine the best parameters for an airborne radar windshear detection system.

An analytical performance assessment of the NASA windshear radar was conducted.[10] This study showed that the NASA radar could detect microbursts with 0 dBZ or greater reflectivity and achieve a missed alarm probability per encounter of 10^{-5} at an approximately 2 km range. The detection range could increase to beyond 5 km if reflectivity increased to above 5 dBZ for a constant missed alarm probability.

Based upon these research simulation studies, Rockwell Collins modified a Model 708 X-band weather radar system to NASA specifications, which allowed research variation and output of basic radar parameters. NASA then designed and integrated a complete radar operation, processing, display, and data recording station. This station was installed on the TSRV for flight test validation.

During the 1991 and 1992 flight tests, the airborne radar detection system identified and tracked high hazard areas. Predicted F-BAR values and real-time alerts were generated which correlated extremely well with airplane in-situ measurements for the microbursts encountered. The radar's F-BAR calculation exceeded 0.06 for 47 microburst events. The radar-based calculation of F-BAR for these events correlated with the in-situ calculated F-BAR at 92% correlation as shown in Figure 1.[11] All radar-based hazard alerts were generated with significant (up to 60 seconds) advanced warning. Windshear was detected in conditions where heavy rain was falling between the sensor and the microburst event. Windshears were also detected for "dry" microbursts with reflectivity in the 5-15 dBZ range. Overall, the performance of the radar system was extremely encouraging.

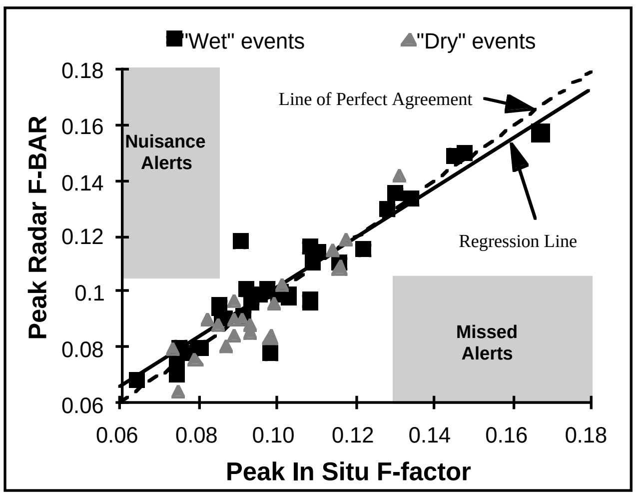

Figure 1 -- Radar Flight Test Performance

Lidar

The primary goal for the airborne lidar was identical to that for the airborne radar. In clear air, laser energy is reflected efficiently by aerosols (small particulates) in the atmosphere. However, laser energy is attenuated by humidity and rain, and usable range given "wet" conditions is the primary limiting factor for lidar system windshear detection applications. The emphasis in airborne lidar development was on those microbursts containing zero or small amounts of liquid water. Since the lidar beam does not increase in diameter appreciably with range, ground clutter is not a problem as it is for radars.

At the beginning of this program, ground-based lidar systems had been demonstrated and used extensively for wind measurement, but airborne lidar system technology was in its relative infancy.

Performance requirements for lidar system designers for windshear detection included:
(a) wind measurements with an accuracy of at least 1 m/s;
(b) range measurement resolution of 75-300 meters;
(c) total range of 2-4 km; and
(d) sector scan of approximately ±20° centered about the airplane flight path.

Extensive trade-off and performance studies were conducted to assess the capability of an airborne lidar to meet performance and operational requirements. Given the technology options available at the time, the decision was made to build a CO_2 system operating at a wavelength of 10.6 μm for the NASA/FAA Airborne Windshear Program. This decision was made even though it was recognized that a Tm:YAG solid-state system operating at a wavelength of 2.02 μm was "on the horizon" as a soon-to-be available technology. NASA considered it more important to evaluate a lidar system as part of this program than to wait an indeterminate period for the "best" technology to become available (also, delaying the entire program, given the need, was not really an option).

The lidar system used in this program was developed by Lockheed Missiles and Space Company to NASA specifications. The system was installed and checked during the winter and spring of 1992 and fully flight tested during the 1992 flight tests. The actual laser hardware consisted of a 10.6 μm (CO_2) laser with an average emitted power of approximately 8 millijoules and configured as a Class I eye-safe system. The laser turret underneath the TSRV forward cargo bay typically scanned ±20 degrees in azimuth and could compensate for attitude changes with approximately 4 degrees of positive pitch and 15 degrees negative pitch. During takeoff and landing operations, the turret was rotated 180 degrees into a protective aerodynamic fairing attached behind the turret.

In the 1992 flight tests, the lidar detection system showed acceptable performance in the "dry" microbursts of the Denver environment. Accurate real-time alerts for several Denver events showed the instrument was capable of measuring windshears several kilometers ahead of the airplane. The lidar's F-BAR calculations were compared with the in-situ windshear detection algorithm (described above) for 13 events as shown in Figure 2.[30]

Significantly degraded performance for the lidar was seen in the much "wetter" Orlando environment. Measurement range in 70-80% humidity conditions was 4 km outside storm cells, with little penetration of storm cells having rainfall rates of 3-4 in/hr. The measurement range in 0.5 in/hr rain was 2 km. The lidar did not produce any alerts in Orlando, although there were many windshear events in which the F-factor exceeded the hazard threshold of 0.105. A number of reasons for this exist:[32]
(a) The 10.6 μm laser had performance limitations that were magnified by the humidity and heavy rains. Key

limitations include the laser's susceptibility to water vapor absorption and its 300 meter range resolution (see next reason).

(b) The lidar's short sensing range in the Orlando environment did not allow a sufficient number of range bins to calculate F-BAR in many cases.

(c) The laser system's pulse energy was diminished by at least a factor of two, due to a failure of a tube in the RF power supply.

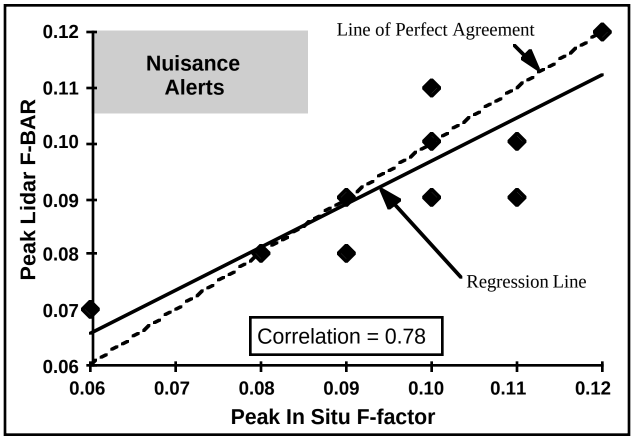

Figure 2 -- Lidar Flight Test Performance at Denver

Considering their experiences in this program, Lockheed subsequently approached NASA and proposed a joint-funded program to develop and test a 2.02 µm solid-state coherent lidar system. The 2 µm lidar system offers advantages of compactness, performance, and reliability over the 10-µm lidar technologies, as well as being inherently eye-safe. Reference 32 describes the 2 µm lidar system in additional detail.

Flight Management

This element of the NASA/FAA Airborne Windshear Program was used to define operational concepts in the context of understanding the hazard (see Hazard Definition).

Airplane Recovery Strategies were investigated to determine the best piloting strategy for minimizing airplane energy loss in the event a microburst is inadvertently encountered. Using TDWR Information on the Flight Deck was investigated to assess the feasibility and issues associated with this approach, which might be an attractive windshear protection option for airplane operators without an installed weather radar. Finally, Crew Information and Procedures for Forward-Look Sensor-Equipped Airplanes were developed and refined to address how this new technology would be integrated in the airplane flight deck and used in the National Airspace System.

Airplane Recovery Strategies

Several studies were conducted at NASA Langley to determine the pilot control strategy that results in minimum airplane energy loss when a microburst windshear is inadvertently encountered. These studies included both batch and piloted simulations.

Three fundamental piloting strategies were examined:[14]

(a) Windshear Training Aid or Manual: This strategy was designed to be used in the absence of flight director guidance. The pilot was instructed to set maximum rated thrust and rotate the airplane toward an initial pitch attitude of 15 degrees. If this pitch attitude did not result in level or climbing flight, then the pilot was to further increase pitch attitude in small increments, while respecting stick-shaker, and hold the required pitch attitude until a positive rate-of-climb was attained.

(b) Flight Path Angle: This strategy required the airplane to fly a flight-path angle that was a function of initial flight path angle, altitude, windshear F-factor, and available airplane performance. Below a reference altitude, the strategy attempted to climb regardless of windshear strength, under the assumption that obstacles must be cleared.

(c) Glide Slope: This strategy attempted to emulate the characteristics of optimal approach abort trajectories. These optimal trajectories had the general characteristic of initially producing a descent and then transitioning to a level flight path that was flown until the microburst event was exited.

These studies indicated that the factor that most strongly affected a microburst windshear recovery was the time at which the recovery was initiated. In piloted simulations, the average recovery altitude only varied by about 20 ft between the recovery strategies tested. In contrast, the average recovery altitude varied almost 300 ft when the initiation time of the recovery strategy was advanced by 5 seconds.

Using TDWR Information on the Flight Deck

The FAA has installed (and continues to install) ground-based Doppler radar systems for windshear detection at major terminal areas around the United States. The Terminal Doppler Weather Radar (TDWR) produces a display used by Air Traffic Control (ATC) personnel that identifies areas of wind divergence (above a threshold value) in proximity to runway approach and departure paths. ATC personnel then include windshear caution/alert and strength information (in the form of "speed loss") as part of take-off and landing clearances. A typical ATC clearance with this information would be, "Cleared for approach Runway 17, microburst alert, 40-knot loss, 3-mile final."

As part of the NASA/FAA Airborne Windshear Program, NASA investigated methods of automatically transmitting and displaying TDWR-derived windshear measurements in an airplane via ground-to-air datalink. To use this information on the flight deck, airborne processing of TDWR information (not originally intended for this application) with other airplane sensor data allowed TDWR-based F-factor hazard information to be computed and displayed. Several technical challenges existed with this approach, including a microburst's changing dynamics between TDWR updates (each minute), and dynamically correcting for the difference between TDWR beam height and the airplane's altitude.

An automatic datalink using VHF packet radio equipment was implemented on the TSRV. Wind divergence location, magnitude, extent and other information were transmitted to the airplane for further processing and on-board display.

During the 1991 and 1992 flight tests, the airborne processing and display of uplinked TDWR data was demonstrated as a feasible and useful automatic windshear information system.[15] Figure 3 shows the flight test data correlation of TDWR predicted F-BAR with the peak in-situ F-factor experienced by the TSRV during microburst penetrations.

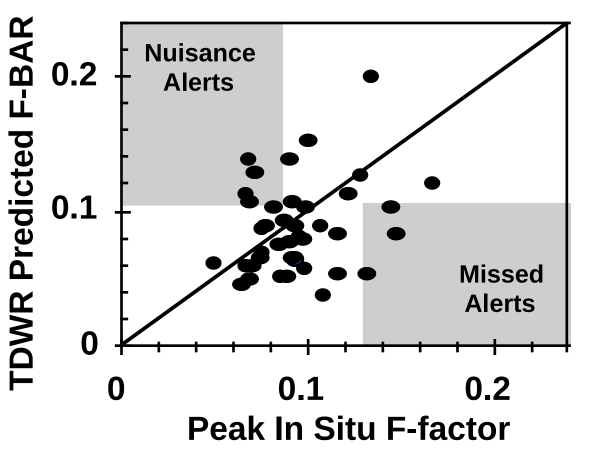

Figure 3 - TDWR Overall Flight Test Performance

The TDWR datalink was used operationally during the flight tests to locate microbursts and maneuver the TSRV to penetrate the event. However, airborne sensors provided the best fine-tuning of the flight path to enable the TSRV to fly through the strongest part of the microburst "core." For several reasons, TDWR information was viewed as more appropriate for microburst awareness and advisories, rather than as a level 3 flight deck windshear alerting system. These reasons include:

(a) TDWR data was only updated once per minute.
(b) TDWR generated icons encompassed the entire outflow region, rather than just the high shear region.
(c) F-factor was calculated by combining TDWR data from one altitude (determined by beam elevation and range) with airplane data at a different altitude.
(d) At most large airports, it is impossible to locate a single TDWR to have adequate coverage of all approach/departure paths.

Crew Information and Procedures for Forward-Look Sensor-Equipped Airplanes

Several crew procedure/display issues have surfaced during the development of forward-look windshear sensor technologies. The issues can be summarized as "what flight crew response is required in a windshear encounter situation and what information must be presented to the crew to enable that response?" Since a significant microburst encounter statistically occurs "once in a career" for the average airline pilot, the information provided to the flight crew and its use should be intuitive, simple, and unambiguous. Three key questions emerged:

(a) At what distance from a windshear hazard should a forward-look system provide information or an alert to the flight crew?
(b) When should a flight crew elect to escape using a lateral maneuver versus escape with a straight ahead climb?
(c) How should existing windshear pilot training be modified for forward-look sensor systems?

In the early phases of the program, various beliefs and opinions existed regarding how the above questions should be answered -- however, no scientific data existed.

NASA Langley Research Center conducted or sponsored several studies that were aimed at addressing the key questions described above. These studies ranged from paper analyses of airplane flight mechanics through and including piloted simulations using realistic microburst models and candidate display formats. A key assumption in these studies was that the microburst events existed independent of other thunderstorm hazards, and that pilots would continue to use current techniques to avoid areas of known heavy rain, hail, and frequent lightning, independent of any windshear threat.

Several decisions made by the FAA/industry working group (see Technology Transfer) also influenced NASA's studies. In many cases, these decisions were made with NASA input. The majority of these decisions were made based upon what has been learned about microburst behavior and the characteristics of forward-look windshear sensors. These decisions included:

(a) Graphical display of microburst alerts would be as icons, since real-time interpretation of a range/azimuth map of F-factor would be difficult.
(b) Icons would only be displayed and alerts would only be provided for events that exceed the hazard threshold, not for detected windshears below hazard strength.

A major issue examined was whether the most appropriate maneuver, at various alert distances from a microburst, is a straight-ahead go-around (or takeoff departure) or an evasive turning maneuver. The results clearly indicated that if there was sufficient distance to avoid a microburst by turning, the turn was not required to successfully escape the microburst event. In other words, when the microburst was 1.5 miles or less away, the best escape maneuver was a maximum performance go-around or takeoff departure. At very long detection distances (greater than 9 miles), flight path changes could often lead to unnecessary traffic flow interruptions at congested airports. These unnecessary traffic flow interruptions would occur if airplanes deviated to avoid a windshear hazard that diminished (due to microburst decay) before they arrived.

The crew procedure proposed by NASA was an extension of the FAA windshear training aid that was in effect at the time. NASA's proposed procedure placed level 1- 3 alerts as precursor, cascade events that would trigger appropriate responses before a reactive (in-situ) windshear system alert. A level 1 alert (advisory) prompted the crew to be aware and consider precautions, but continue on the current flight path. A level 2 alert (caution) required crew action to prevent a low-energy encounter, but negotiation with ATC for path deviation was possible. A level 3 alert (warning) required the crew to immediately execute a straight-ahead, maximum performance climbing maneuver to assure airplane survival. These procedures and alert levels were proposed with no specific technology in mind and all procedures/alerts may not be appropriate to every technology.

A piloted simulation study was conducted using the above crew procedure with three display options:[5]

(a) No icon display.
(b) A microburst icon was displayed independent of alert level.
(c) Three-level microburst icons that corresponded to the crew procedure -- a different color for each of the three alert levels.

In terms of recovery performance, there were no statistically significant differences among the display types. However, pilot subjective ratings clearly indicated their unanimous preference for icon displays. Almost all of the pilots had a slight preference for the three-level icons. All pilots indicated that the procedure was acceptable, but they did not always follow it.[5]

The crew procedure and display evaluated by NASA was similar, but not identical, to the standard that has been since adopted by the industry working group (see Technology Transfer). The working group defined a level 3 alert region that is smaller than the one evaluated by NASA except on takeoff roll -- when the region is extended to double the range and 1/4 mile on each side of the extended airplane heading vector. The level 2 alert region defined by the industry working group is also smaller than the alert region evaluated by NASA. The industry working group definition allows some systems to omit this level altogether.[16]

While some debate remains over the preferred crew procedure for a level 3 alert on approach, the current standard is a published go-around maneuver using go-around thrust with normal airspeed schedules for gear and flap retraction. This provided the best energy state for microburst penetrations in all but the most extreme cases of a late alert and an intense windshear over a small area. The industry is currently debating whether crews will confuse an in-situ alert with a forward-look alert, resulting in a crew reconfiguring their airplane after microburst entry. This would have negative consequences, and this possibility has led to suggestions to use the current Training Aid procedure as the appropriate crew response to all windshear alerts.

A final issue that was identified by NASA is that valid forward-look windshear system alerts may be perceived as nuisance alerts. This concern was based on the fact that a successful forward-look windshear detection and crew response will lead to the airplane encountering the microburst event at a greatly increased energy state. The resulting transit of the event will be a much less noteworthy experience, either due to higher airspeed, higher altitude, or both. At higher airspeeds, the effect of horizontal wind fluctuation is relatively less and the hazardous windshear exposure time is significantly reduced. At higher altitudes the microburst is mostly downward-moving air, with little outflow and therefore little horizontal wind fluctuation. In summary, the concern is that pilots, having been alerted by the system, might conclude that the system had issued a false alarm if (as hoped) the microburst penetration was not eventful. The FAA/industry working group concluded that this must be part of the training -- pilots must be told to expect that a successful forward-look windshear detection may lead to a subtle microburst encounter.

Flight Test Validation

A fundamental philosophy that shaped the design and operation of the flight tests was the use of the in-situ algorithm as the 'truth' measurement of windshear magnitude. Thus, a forward-looking sensor in continuous operation could compare predicted windshear hazard values with in-situ measurements as the airplane flew through or near a position in space previously sampled by the remote sensor. Close agreement between a forward-looking sensor measurement and the corresponding in-situ measurement would confirm two hypotheses:

(a) The sensor can accurately measure windshear hazards from a remote distance.
(b) Microburst windshears evolve slowly enough that an accurate remote measurement 3-5 km in front of the airplane is a reasonable estimate of windshear intensity 30 to 60 seconds in the future

Both of these hypotheses must be true for a viable forward-looking windshear detection system.

The specific goals of the flight test program were threefold. First, the operational feasibility of TDWR/airplane data communication and the performance of an airborne algorithm to process TDWR data into windshear information was to be evaluated and demonstrated. Second, clear air airborne radar ground clutter measurements were to be collected at multiple airport locations along different runway approach paths to assess moving and fixed ground clutter suppression techniques. Finally, the most difficult and critical test was to evaluate the windshear detection performance of the infrared, radar, lidar, and in-situ systems in actual atmospheric and operational conditions.[17]

The flight test program was successful. During the 2-year flight test period, the TSRV performed low-altitude (750 to 1100 feet) penetrations of more than 75 microburst windshears and strong gust fronts. The airplane flew through heavy rains and dust clouds, near hail and frequent lightning; all in proximity to major airports without any safety incidents. This was due in large measure to the strong cooperation of ATC personnel at Denver and Orlando, as well as participation of two organizations that operated ground Doppler radar units at each test site.[18] The National Center for Atmospheric Research operated the Doppler "Mile High" radar at Denver running TDWR algorithms, and MIT Lincoln Laboratories operated a prototype TDWR at Orlando. A huge volume of unique and valuable data from each of the research sensor systems was collected.

The maximum in-situ windshear measured reached an F-factor hazard index level of 0.17, well in excess of the alert threshold for commercial airplane reactive sensors (F-factor equal to 0.105).[6] Seventeen other microburst penetrations triggered in-situ alerts. The tests also revealed sensor performance characteristics in both extremely "wet" and "dry" meteorological conditions. Over the 2 years of flight testing, the TSRV penetrated 56 "wet" (>35 dBZ) microbursts and 19 "dry" microbursts. All of the "dry" microbursts were obtained in 1992 in the Denver area. Additionally, strong low-reflectivity gust front windshears were recorded that provided additional "dry"-type windshear data. The maximum performance *increasing* shear penetrated at Denver reached an F-factor of -0.24.

The airborne and ground-based sensor systems acquired outstanding high resolution measurements of microburst dynamics and structure. For the first time, an in-situ measurement of hazardous windshear was correlated with other independent measurements. Also, an airborne radar and airborne lidar detected and accurately measured areas of hazardous windshear.

Additional flight test operations notes are listed below:

(a) The TDWR datalink, airborne processing and display, coupled with a research differential GPS system for precision navigation, were critical in guiding the TSRV to microburst events of interest and maximizing the probability of penetrating the "center" of a microburst.

(b) Visual indications of windshear strength were not apparent, though at times a bowing out of the rainshaft shape due to low-altitude divergent winds was observable. However, at other times, the microburst was embedded within multiple rain cells and a distinct shape could not be observed. Additionally, many microbursts and gust fronts penetrated in the Denver area were essentially clear air phenomena with little or no associated visible moisture.

(c) Advance knowledge of the location/strength of windshear events, coupled with entry airspeeds of 210 to 240 knots, was sufficient for the TSRV to experience the energy loss of the penetrated windshears with little altitude loss. This was expected and confirmed piloted simulation results and flight mechanics analysis.

Technology Transfer

From its inception, the NASA/FAA Airborne Windshear Program emphasized the transfer of technology products generated by NASA to appropriate groups within the FAA and in industry. This was accomplished in many ways. Although it would be impossible to discuss each way that technology generated by NASA (or developed under its sponsorship) was transferred, a few were noteworthy.

First, NASA and FAA hosted 5 "manufacturers' and technologists'" workshop/conferences beginning in 1987 and ending in 1993. These workshops were a forum for all parties interested in remote detection of microburst windshear to convene and review the technical progress that had been made since the last conference and the technical issues that remained. Conference sessions were informal, with presentation charts, lively questions and answers, and daily panel discussions that were often quite spirited. The presentation charts, as well as transcriptions of question and answer exchanges (the latter only for the last few conferences) were published as NASA/FAA reports.[1-5]

Second, personnel from NASA and its contractors participated in several government/industry efforts to develop standards and guidelines for forward-look windshear detection systems. NASA personnel participated on an RTCA Special Committee developing windshear radar minimum operating performance standards (MOPS). NASA personnel worked very closely with FAA certification personnel as described below.

FAA Certification

A working group was formed to develop system level requirements and a certification methodology for forward-look windshear detection systems. This group consisted of personnel from FAA certification and research offices, NASA Langley Research Center and its support contractors, the airlines listed under FAA exemption 5256, avionics vendors, and airframe manufacturers. This working group catalyzed a tremendous amount of technology and knowledge transfer from NASA and

NASA-funded contractor personnel to the FAA and industry.

The clearest manifestation of the value attached to NASA's technology contributions was the FAA's request that NASA Langley Research Center develop an event database for use in forward-look windshear detection systems certification. The event database, containing seven windshear cases generated by TASS, encompasses a wide range of events suitable for testing and certification of forward-look windshear sensors. The general certification process involved vendor-developed and -validated sensor simulation software and vendor-collected ground clutter data integrated with the event database to demonstrate, in simulation, detection performance in a variety of meteorological conditions. Successful completion of this demonstration is required for FAA certification.

While developing the event database, NASA and its contractors also applied the certification methodology to the NASA experimental windshear radar. NASA's effort to exercise and validate the methodology provided valuable lessons learned and insights to both the FAA and avionics vendors who were developing systems that were nearly ready to initiate the certification process.

In June 1996, three vendors -- Allied Signal Bendix, Rockwell Collins, and Westinghouse Electric -- produce certified forward-look windshear radar systems. Over 2000 orders have been placed for these systems from foreign and domestic carriers and the U.S. Air Force. Continental Airlines became the first carrier to operate a windshear radar in revenue service in 1994. Airbus is about to deliver aircraft to United Airlines that are factory-equipped with windshear radars. Boeing and McDonnell Douglas are in the process of integrating windshear radars in their production aircraft as factory-installed options. Strong interest has been shown by foreign carriers, particularly in the Asian market, for factory-installed windshear radars in new aircraft. One vendor currently ships about 40% of its new X-band radars with the windshear function. Within 3 years, this vendor expects to ship nearly all of its X-band radars with windshear capability.

Reconstructing a Microburst Encounter

On July 2, 1994, USAir Flight 1016, a DC-9 on approach to landing at Charlotte's Douglas International Airport, unexpectedly encountered a rapidly intensifying microburst just seconds before it was to touchdown on runway 18R. The airplane crashed after encountering strong windshear, killing 37 of the 57 persons on board. The pilots apparently did not recognize the windshear condition (which was severe) in time to prevent the accident. Neither the airplane's certified in-situ windshear detection system nor any ground-based systems (Charlotte has an ASR-9 weather radar and a Phase-2 Low-Level Windshear Alerting System) provided any warning to the flight crew of Flight 1016.

To support NTSB analysis of the accident, this microburst event was reconstructed using numerical results generated by TASS. The TASS numerical simulation was initialized with an atmospheric sounding representing Charlotte's meteorological environment near the time of the observed microburst event. TASS produced a microburst event that agrees well with the meteorological observations made of this storm.[29]

An analysis of the winds from Flight 1016's flight data recorder was provided to NASA by both McDonnell Douglas and the NTSB. These datasets were slightly different since McDonnell Douglas and the NTSB used different methods to compute the winds from the available flight data recorder parameters. Both the calculated along-body winds and the F-BAR hazard index from the flight data recorder data and TASS showed good agreement. This microburst was unusually intense, yielding an F-BAR of about 0.3.

The NASA radar simulation was coupled with the TASS numerical data for this microburst event. The simulated radar was a modern, X-band weather radar that employed NASA-developed processing algorithms -- based on the radar tested during the NASA flight tests. The radar simulation was configured for an approach to Charlotte's runway 18R using the TASS database and a ground clutter dataset gathered in Philadelphia. Charlotte clutter data were not available and the Philadelphia clutter environment was considered a good challenge for the radar. In spite of ground clutter, the simulated radar was able to identify the microburst hazard and issue a warning more than 30 seconds before the windshear encounter. From these radar simulation results, we concluded that an airplane on approach with this microburst configuration could have received adequate warning if equipped with a windshear radar.[29]

Concluding Remarks

NASA and FAA formed a partnership with each other and the aviation industry to investigate the feasibility of remote airborne windshear detection. A multidisciplinary team of NASA researchers and NASA-funded contractors developed (or fostered) the necessary concepts, methods, and tools required to demonstrate airborne forward-look windshear detection technology. The multi-year effort was extremely intense for the participants and shows what results can be achieved when NASA's technical expertise is focused on a high priority aviation challenge. It is our view that the NASA/FAA/industry partnership was very successful, since the technology now exists to eliminate microburst windshear as a commercial aviation hazard.

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